Session 4
Developing Drag

1.0 Definitions

Coefficient of drag (C_D) - A measure of how much of the dynamic pressure gets converted into drag.

****START VIDEO****

2.0 Introduction

The previous section started with a discussion of the change in momentum of a particle of air. As the air hit the wing, its new trajectory was split into two components; one parallel to the original direction (relative wind) and one perpendicular to it. The new perpendicular momentum was shown to be related to the lift. The change in horizontal momentum was mentioned only briefly. The emphasis of this session is to correlate this change to *profile* drag.

Caution:

An airplane must fight its way through *two* kinds of drag in order to maintain steady flight; profile drag is the same kind of drag experienced from all objects in a flow. Cars, rocks, and hockey pucks must all overcome profile drag. Objects that create lift must also overcome *induced* drag, also known as drag-due-to-lift. Discussions of induced drag are saved for later. The video footage uses the word "drag" instead of "profile drag."

The concepts from the previous session all apply to drag, so many of the calculations are repeated as well. As before, the aerodynamic force generated can be calculated as the rate of change of momentum. Since drag is defined to be along the direction of the relative wind, then we need only to look at this component of momentum.

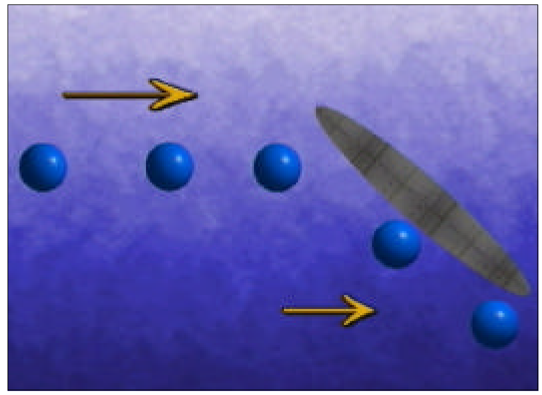


Figure 4.1 Change in Momentum

Figure 4.1 shows that the air particle's horizontal momentum decreases as it moves along. Since its mass isn't changing, we can conclude that only the speed is decreasing. The profile drag is the mass times the deceleration (of the air).

$$Profile\ Drag = m \times a_{horiz} = m\frac{\Delta V_{horiz}}{\Delta t}$$

The cause of this deceleration is the loss of energy from skin friction and from pressure.

3.0 Skin Friction

Skin friction is a function of the surface area wetted by the airstream. Any increase in surface area will increase skin friction drag. In addition to this area in contact with the flow, skin friction drag is also affected by what's happening at the contact point between the fluid and the surface. More specifically, it is affected by the fluid's speed and viscosity (stickiness) and by the roughness of the surface.

NOTE:

The Operational Supplement at the end of this session defines the various types of friction.

Some of these effects can be demonstrated with experiments. To eliminate the effect of pressure drag, we need to use an object with constant weight and aerodynamic properties. A puck from an air hockey table should work nicely.

To determine how much skin friction drag exists, we must measure the force needed to overcome it. Place the puck on a flat piece of sheet metal or a smooth board (Figure 4.2). If you tilt the board slowly at an increasing angle until it starts to move, the weight of the puck will overcome the **Breakout Friction**. This is of course greater than the running friction.

Since aircraft skin friction is more like running friction, it would be appropriate to show this measurement with the puck. To do so, tilt the board, hold it, slide the puck slowly and see if it continues at the same speed. If it slows down, tilt the board more and try again. If the puck accelerates after the push, the reduce the tilt of the board and try again.

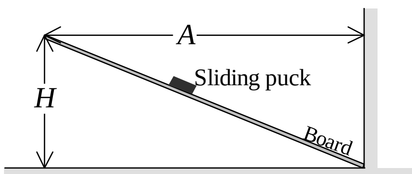


Figure 4.2 Coefficient of Friction, $C_f = \tan\ c = \frac{H}{A}$

Since the puck's weight increases the friction force **and** the propelling force, the weight effect essentially cancels out and the tangent of the angle of the board is used to define the friction coefficient.

With a measurement capability in place, we can show the effect of changing fluid viscosity. With the dry board as a baseline measurement, reduce the viscosity by adding a light oil or running water to the board. Once the puck starts moving, much less tilt is needed to keep it going. The test can be repeated with a thick, high viscosity fluid such as grease or molasses and will show a need for higher tilt. An extremely low viscosity fluid such as air requires very little tilt at all: If an air hockey table is turned on, the puck will barely slow down at all once set in motion. Only a very slight tilt is needed to keep the puck moving at constant velocity.

To illustrate the impact of speed on skin friction drag, this same series of experiments can be repeated with a higher initial velocity on the puck. Keeping the puck moving at a constant high speed requires only a little more tilt (compared to the low-speed tilt) on an air hockey table, but requires a lot more tilt when using a more viscous fluid. The increase in required tilt angle demonstrates the fact that the speed of the flow also affects the drag. Technically, some of the increase in tilt is due to the extra pressure drag at the higher speed, but this is such a small difference at the low speeds in this experiment that it is practically unmeasureable.

To demonstrate the effect of surface roughness, the experiment can be conducted with a highly polished board (or glass), a rough board, and a board with sandpaper. The above series of experiments can be conducted with a large combination of speeds, roughness, and fluids.

Since aircraft only fly in air, skin friction is due only to the speed and skin roughness. Many race pilots and ground crews spent time waxing their planes to get the smoothest possible surface.

NOTE:

There is a small change in the viscosity of air as it warms up. Unlike liquids, air actually gets more viscous as it heats up. The difference is not significant for general aviation aircraft like Cessnas and Beechcraft, but is more important for fast-movers like the Concorde and SR-71 because they fly so fast that they heat the air around them.

4.0 Pressure Drag

The other component of profile drag is pressure drag. Pressure drag is a function of the size of the wake behind an object in an airstream; it can be reduced by streamlining the object in order to delay separation of the flow. A side effect of streamlining is an increase in the wetted (exposed) area and hence the skin friction, so it is important to ensure that a net reduction in drag is actually achieved when adding streamlining. Figure 4.3 compares the drag coefficients of various shapes which are immersed in the same airstream.

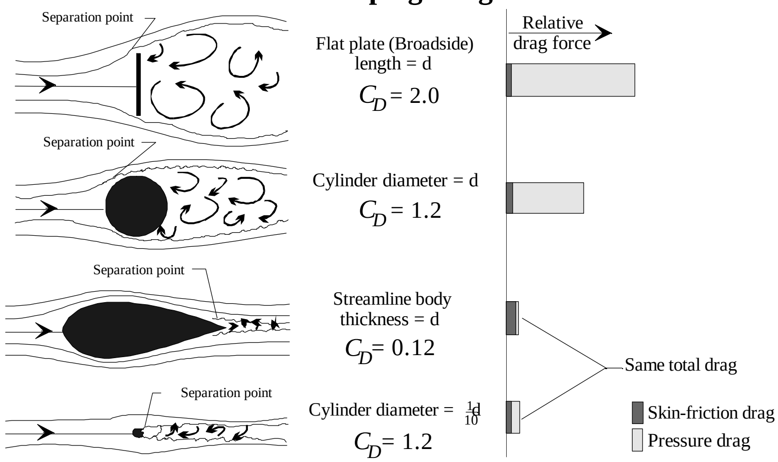


Figure 4.3 Drag Coefficients of Various Bodies

The flat plate has almost no skin friction drag because the flow is attached to the plate only a short distance at the edge. The plate does, however, generate a strong, turbulent wake, so pressure drag is very high. Because a flat plate normal to the airstream creates so much drag, aerodynamicists avoid such additions to aircraft or automobiles.

Figure 4.4 Large Flat Plate

The "blunt" motorhome is a good reminder that designers sometimes must make compromises to have an all-around good package. The C-23 Sherpa aircraft looks blunt from the front view, but is shaped enough in the side view to allow it to fly at 200 mph.

If a cylindrical cross-section is used instead of a flat plate, the airflow stays attached to the surface almost to the shoulder producing more skin friction drag. When the strength of the wake is reduced, so is pressure. The diagram shows that the total drag is 40% lower than that of the flat plate.

Proper streamlining of the same basic diameter reduces the total drag to 6% of the flat plate drag. The skin friction component is almost four times as large as in the flat plate's friction but, because the flow stays attached for almost all of the surface area of the streamlined shape, the wake and, therefore, the pressure drag, are minimized.

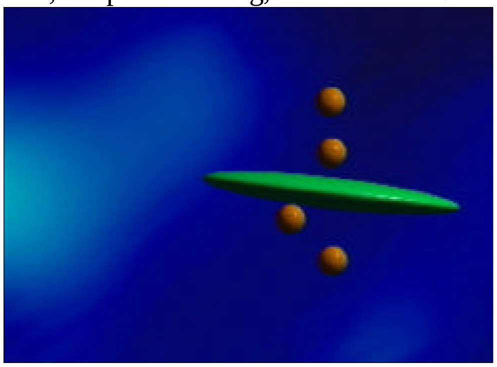
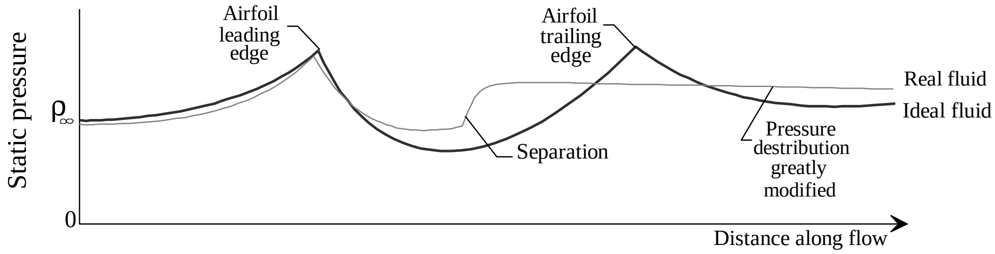


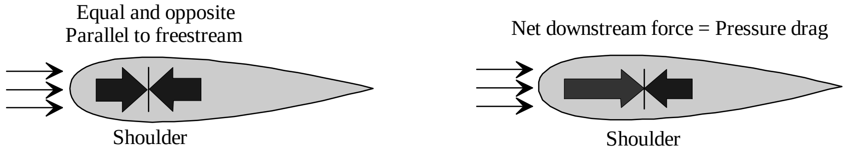
Figure 4.5 Streamlined Shape

4.1 Causes of Pressure Drag

If there was no such thing as friction, then the flow across a surface would retain its original energy and wouldn't separate from the surface. If this was true, then the pressure change across an airfoil would look like the ideal curve in Figure 4.6(a). This ideal situation is called "total pressure recovery" since the pressure at the trailing edge is the same as that at the leading edge. In this ideal situation, all the pressures acting in the drag direction are exactly offset by the pressures in the thrust direction (Figure 4.6(b)) and therefore, no drag exists. Our experience tells us this ideal case does not exist.



(a) Airfoil upper surface static-pressure distributions



(b) Ideal fluid air foil (no pressure drag) Sum of horizontal pressures = 0

(c) Real fluid airfoil (net pressure drag) more drag pressure than thrust pressure

Figure 4.6

reality, friction robs some of the energy of the flow (transforming it into heat and noise). When this happens, the flow will have insufficient energy and will separate from the airfoil surface. The actual pressure within the separated flow is typically random and changes quickly, but averages out to be the same as atmospheric pressure. This is illustrated as the line for the real fluid in Figure 4.6(a).

Since there is not total pressure recovery at the trailing edge, a pressure differential will exist between leading and trailing edges. This pressure differential will produce a retarding force called pressure drag (Figure 4.6(c)). For any given airspeed, the pressure drag is essentially proportional to the size of the wake behind the body. The force also increases with the square of velocity, (Figure 4.7).

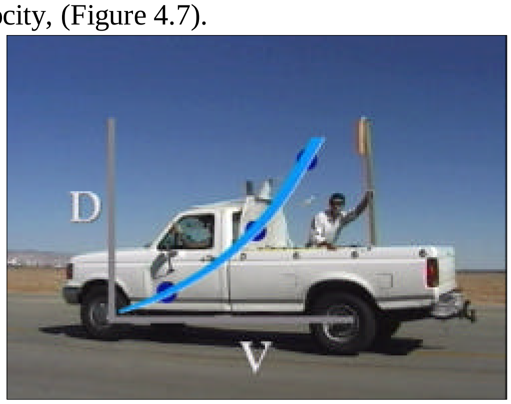


Figure 4.7 Drag Increase with Velocity

When the Wright Brothers were designing the first airplane, they needed to determine what shapes gave the lowest drag. Instead of trying to measure the actual drag force in pounds, they placed the test article on one end of a weathervane device and placed a flat plate on the opposite end at the same radial distance. The entire unit was placed inside a wind tunnel. The wind was forced through the tunnel by a fan after being straightened by a simple grid. The straightened flow then blew on the weathervane which pivoted about its vertical axis. For each shape tested, they increased or decreased the size of the flat plate until its drag force was the same as the shape. They knew the drag forces were equal when the weathervane didn't move when released. With this method they determined the "equivalent flat plate area" drag for a great many airfoil and propeller shapes, (Figure 4.8).

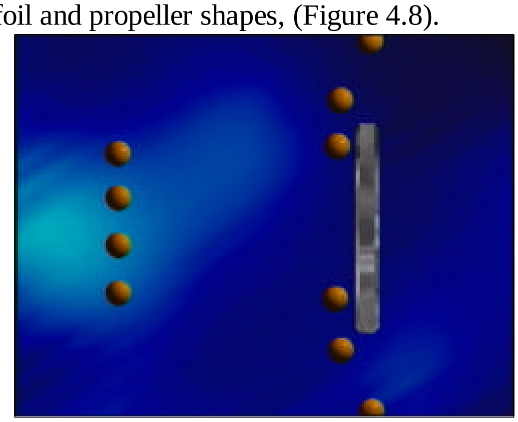


Figure 4.8 Equivalent Flat Plate Area

The Wright Brothers were very careful to eliminate unwanted effects. They made sure there were no other drafts in the room, and nothing upset the delicate test rig. Section 7 of this session describes an experiment similar to that performed by the Wright brothers.

5.0 Summary

The students should realize that the total change in momentum yields a total force called the resultant aerodynamic force (RAF). This is vectorally divided into the more common lift and drag forces (Figure 4.9). There is nothing special about the drag force, it is still measured as the rate of change of momentum - just in the drag direction. An aircraft designer tries to arrange the shapes so the RAF points in the lift direction as much as possible.

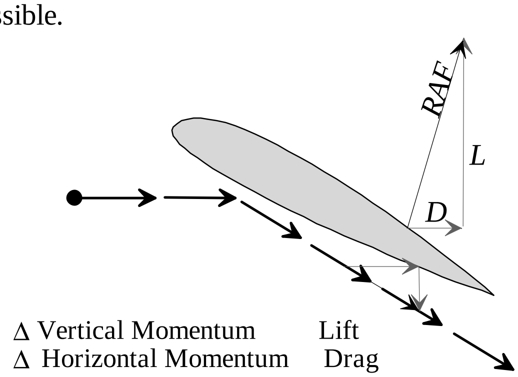


Figure 4.9 Resultant Aerodynamic Force

Figure 4.10 Overall Drag Equation

6.0 Measures of Performance

1. If an object's speed is tripled what happens to its drag?

$$D = C_D \frac{1}{2} \rho V^2 S$$

2. If an airplane flies so high that the air density is only 1/10 of sea level density, then how does the drag compare?

3. What is streamlining?

4. Why are some vehicles not streamlined?

7.0 Suggested Activity

An experiment to demonstrate profile drag can be set up with the same idea the Wright Brothers used.

1) A leaf blower or one or two electric fans (in a row) can be used for power. (Figure 4.11(a))

2) The flow straightener can be made from boxes that are used for shipping wine or beer bottles or food jars. The cardboard dividers inside can be used side-by-side or in a row depending on their size. The airflow can be checked for straightness by taping a few 3" pieces of yarn to the cardboard dividers. (Figure 4.11(b) and 4.11(c))

3) Instead of a weathervane, you can use the front wheel of a small (motocross-type) bicycle. The wheel must have good quality, well-adjusted bearings that rotate freely. The wheel must be mounted so that its axle is perfectly horizontal. The wheel can be mounted separately or by just flipping the bike upside-down and leveling it. A bike wheel is used because it is readily available and has good bearings. Another device with a good axle will work also. (Figure 4.11(a))

4) Attach the test article to the wheel. This can be done at the spokes or the rim. Either way, it is good practice to laterally separate the article from the wheel by a couple of inches to avoid airflow interference. The separating mount is called a sting. The wheel's aerodynamic interference can be further minimized by wrapping cellophane or mylar around it. (Figure 4.11(c))

5) Hook a small container (*w*) to the wheel (at the same radial distance as the sting for simple

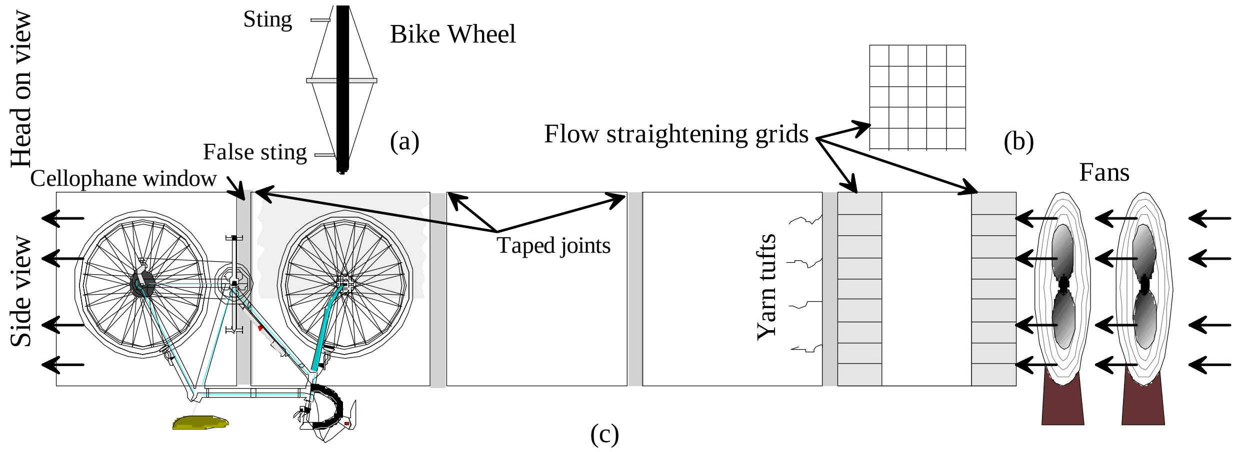


Figure 4.11

calculations). When the test article is at the top (directly above the axle), the weight should be on some point in front of and horizontal to the axle. (Figure 4.12)

6) Next, the wheel must be statically balanced so that it will stay in any angular position in which it is placed. If it isn't balanced, then it will always have a tendency to rest with the heavy side on the bottom. Balancing the wheel is easy: when the heavy end rotates to the bottom, simply tape some weights near the top of the wheel to offset the heavy part.

7) A useful rectangular wind tunnel can be built using cardboard boxes taped together end-to-end. The purpose of the tunnel is to constrain the air so the fan's energy isn't wasted by blowing around the test region. A powerful fan allows the use of a large refrigerator box tunnel, but a smaller fan requires a more narrow tunnel. Both ends must be open. Fans are typically placed so they blow into the tunnel, but some are built so the fan "sucks" air into it. A slot must be cut in the bottom for the wheel. It must be wide enough to allow for the test article as well as the wheel. A small flap may be employed to close especially wide openings. A cellophane window can be cut into the side of the tunnel at the test section. To prevent the wind from spinning only one side of the wheel, the tunnel should be large enough so that the entire wheel fits inside (Figure 4.11(a)). A false sting (aerodynamically similar to the actual sting) should be placed on the wheel opposite to the actual sting.

8) **If** the tunnel is not large enough for the entire wheel, **then** remove the test article only and perform step 6 without the test article. Next, submerge as much of the wheel as practical into the tunnel and turn on the fan. With the sting at the top, place additional "speed weights" on the wheel to prevent its rotation (due to wheel and sting drag). See Figure 4.12. Speed weight balancing must be accomplished for each fan speed setting, After balancing, turn off the fan and install the test article on the wheel and rotate the wheel so the test article is at the top. Be sure the article is fixed at the desired angle of attack.

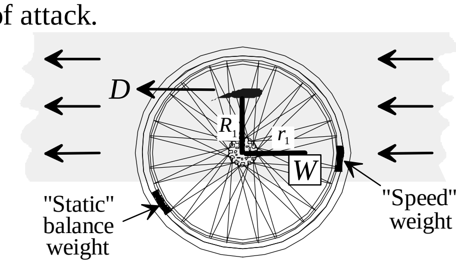


Figure 4.12

9) When the fan is turned on, the aerodynamic drag on the test article tries to force the wheel to turn. This can be prevented by adding some weight (lead shot, sand) to the container.

If the container is placed at the same radial distance as the sting ($R_1 = r_1$), then the weight of the sand is exactly equal to the drag force. If the distances are different, then;

$$\text{Profile Drag} = \frac{\textit{sand weight}(\textit{HORIZONTAL}\text{ distance to weight})}{\textit{VERTICAL}\text{ distance to sting}}$$

We can use this equation to simplify the test procedure: instead of adding and deleting mass from the container, slide the hook (moment arm) to compensate for profile drag.

NOTE:

The test article should be exactly at the top at all times, otherwise it's off-center weight and lift will tend to rotate the wheel as well the change in aerodynamic drag.

10) Repeat the test for different angles of attack and different shapes, i.e., balls, cylinders, model airplanes, flat plates, airfoils, molded clay shapes, etc.

11) If any of the test articles create lift, then they will also probably create their own pitching moment (M) that tends to rotate the wheel. If precise tests are to be done to eliminate this effect, then the test should be repeated with the sting at a different radius (R_2) and the same balancing weight (w) at whatever new radius (r_2) is required to maintain a vertical sting position. This twin test gives two equations with two unknowns, M and D:

$$w \times r_1 + M = D \times R_1$$

and

$$w \times r_2 + M = D \times R_2$$

solving simultaneously yields the profile drag and the pitching moment:

$$D = \frac{w[r_1 - r_2]}{[R_1 - R_2]}$$

$$M = w\left[\frac{(r_1 - r_2)R_1}{(R_1 - R_2)} - r_1\right]$$

With the wheel rotated so the sting is directly in front of the axle, weight can be tied to the sting to determine the lift of the airfoil section. Again, the weight required will be affected by the pitching moment. The nose-over moment (M) calculated previously can be added to the weight to get total lift:

$$L = w + \frac{M}{\textit{horizontal radius to weight}}$$

Once the experiment equipment is established, a wide variety of tests can be accomplished: lift, drag & pitching moment, measurements; effects of different shapes & surface roughness; the influence of test article frontal area and airspeed on drag.

Such a matrix of tests would be daunting for a single class, but a good local database can be established after only a few classes. Of course it would be important to be able to recreate the same test set-up and retain test article for future classes.

Alternate Approach:

To avoid the destabilizing effect of the test article moving off from the vertical, the test can be rigged with the wheel horizontal (vertical axle).

In this case, the balance weight is connected through a string and pulley. As shown in Figure 4.13.

The "speed weight" test is performed with all parts connected except the test article. When the test article is added, any **additional** weight compensates for the profile drag. This test apparatus is more elaborate, but is easier to work with.

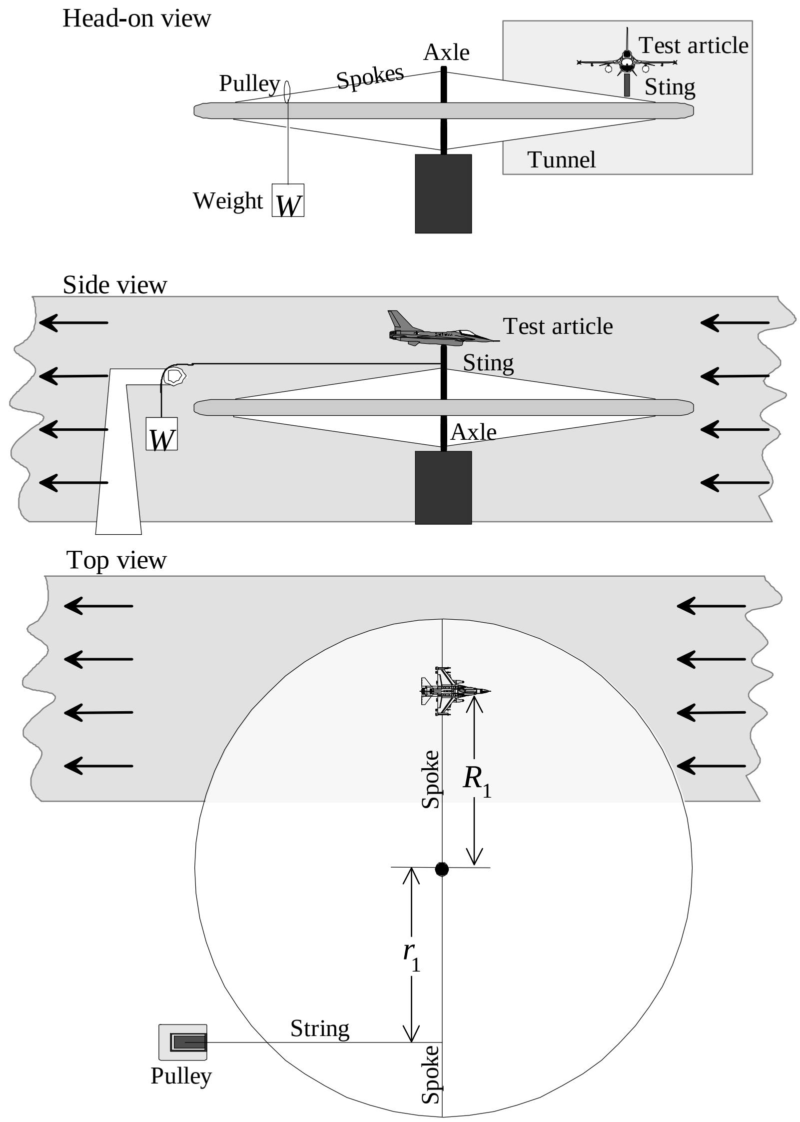

Head-on view
Axle
Test article
Pulley
Spokes
Sting
Tunnel
Weight
W
Side view
Test article
Sting
W
Axle
Top view
Spoke
R_1
r_1
String
Pulley
Spoke

Figure 4.13

Operational Supplement

Friction Forces

Friction forces always act to oppose the motion of one body over another when parts of their surfaces are in contact. These forces are caused by the adhesion of one surface to the other and by the interlocking of the irregularities of the rubbing surfaces. The magnitude of frictional force depends upon the properties of the surfaces and upon the normal force (force perpendicular to the surface). The effects of friction are often undesirable, because friction increases the work necessary to do a task, causes wear in machinery parts, and generates heat. To reduce this waste of energy, friction is minimized by the use of wheels, bearings, rollers, and lubricants. Automobiles and airplanes are streamlined in order to decrease air friction. On the other hand, friction is desirable in many cases. Nails and screws hold boards together by means of friction. Power may be transmitted from a motor to a machine drive-wheel by means of a clutch or a friction belt. In walking, driving a car, striking a match, tying our shoes, or sewing fabric together we find friction a useful tool. Cinders or sand are scattered on icy streets, grooves are cut into the tires of automobiles and aircraft, and special materials are developed for use in brakes - all for the purpose of increasing friction where it is desirable.

Sliding Friction. When we slide a box across a floor, we must continually apply a steady horizontal force to cause the box to slide uniformly over the horizontal surface. Newton's third law states there is a force, parallel to the surfaces in contact, opposing the motion. This opposing force is called *friction.* The frictional force is generally the result of the roughness of the two surfaces in contact, which causes interlocking between them. This interlocking gives rise to a force that resists motion. If the applied force is just equal to the opposing frictional force, the box will continue to move uniformly; if the applied force is greater than the frictional force, the body will accelerate.

The observations we can make regarding sliding frictional force are these:

1. It is parallel to the surfaces in contact.
2. It is proportional to the force which is normal (perpendicular) to the surfaces which presses them together.
3. It is generally independent of the area of the surface contact and independent of the speed of the sliding, provided that the resultant heat does not alter the condition of the surfaces or fluids are not introduced between the surfaces.
4. It depends upon the properties of the substances in contact and upon the condition of the surfaces, e.g., polish, roughness, grain, wetness, etc...

Sliding friction is sometimes called *kinetic friction.*

When one body is in uniform motion on another body, the ratio of the frictional force, F, to the perpendicular force pressing the two surfaces together, N, is called the *coefficient of kinetic friction*, μ. It can be expressed by the following equation:

$$\mu_k = F/N \tag{1}$$

When the two surfaces are lubricated, the lubricant fills the surface irregularities, reducing the friction. The ratio F/N, however, is no longer a simple constant, but, depends upon the properties of the lubricant, the area, and relative speed of the moving surfaces.

Static Friction. When a body at rest on a horizontal surface is pushed gently by a horizontal force, it does not move because there is a frictional force just equal to the applied force. If the applied force is increased slowly, the frictional force increases to oppose motion until a *limiting force* is reached.

Operational Supplement

If the applied force exceeds the limiting friction force, the body "breaks out" into accelerated motion. The *coefficient of static friction* is the ratio of the "breakout" frictional force to the normal force.

$$\mu_s = F_{bo}/N \tag{2}$$

For any two surfaces the coefficient of static friction, μ_s, is somewhat greater than the coefficient of kinetic friction μ_k.

Rolling Friction. *Rolling friction* is the resistance to motion caused chiefly by the deformation produced where a wheel, bearing, or roller pushes against the surface on which it rolls. The deformation of an automobile tire in contact with the pavement is readily visible. Even in the case of a steel wheel rolling on a steel rail, there is some deformation of the two surfaces. The deformation of the two surfaces produce internal friction in the two bodies. The force of rolling friction varies inversely with the radius of the roller, and decreases as more rigid surfaces are used. Rolling friction is ordinarily much smaller than sliding friction.

Viscous Friction. The friction forces encountered by solid objects in passing through fluids and the frictional forces set up within liquids and gases in motion are examples of *viscous friction*. The laws of fluid friction differ greatly from those of sliding and rolling friction. The amount of frictional resistance encountered by an object moving through a fluid depends on the size, shape, and speed of the moving object, as well as on the properties of the fluid itself. The frictional resistance encountered by a man falling through the air increases with his speed until he reaches a terminal speed, about 120 mi/hr, at which time the retarding force of friction equals his weight. When he opens his parachute, the greater surface it presents increases the retarding force of friction and reduces the terminal speed to 14 ft/sec.

Viscosity is that property of a fluid, its internal friction, which causes it to resist flow. Viscosity is due fundamentally to cohesion and molecular momentum exchange between fluid layers, and, as flow occcurs, these effects appear as shearing forces (parallel to the layers) between the moving layers. Consider a layer of liquid in a shallow pan, onto which a flat plate, A, is placed, as shown in Figure 1. A force F is required to maintain the plate at a constant speed V with respect to the other surface B. On the surface of each solid, A and B, there will be a layer of liquid that adheres to the solid and has zero speed. The next layer of liquid moves slowly over the first, the third layer moves slowly over the second, and so on. This distribution of speeds results in a continual deformation of the liquid. This internal (or viscous) friction distorts the cube of fluid, C, into a new shape, R, as the force moves the upper plate.

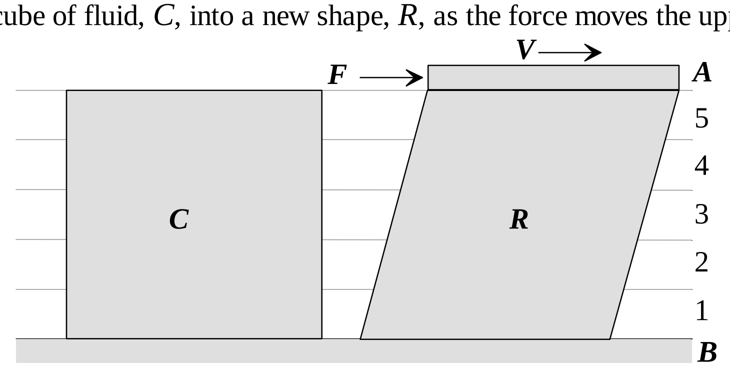


Figure 1 Viscous Friction

The viscosity of liquids decreases with increase in temperature. A liquid that flows as slowly as the proverbial molasses in January at low temperature may pour freely at higher temperature. Lubricating oil may fail to form a desired protective film at low temperatures; hence, when starting a car on a cold day, it is wise to allow the engine to idle for a time until the oil is warmed. The viscosities of gases, unlike those of liquids, increase with increase in temperature. The internal friction of liquids is attributed to the cohesive forces between closely packed molecules. In the case of gases, whose molecules have much larger separations, cohesive forces are much smaller and some other mechanism must be sought for internal friction. This other mechanism is in the form of a continual migration of molecules from one layer to another. Molecules diffuse from a fast-moving layer to a slower moving layer, and from the slower moving layer to the faster. Thus each layer exerts a drag on the other proportional to the mass of the molecules and their speeds. This description of gas viscosity accounts for the fact that an increase in temperature, which increases molecular speeds, results in an increase in the viscosity of a gas.